OPTICAL COMMUNICATIONS FOR NASA's SMALL SPACECRAFT MISSIONS OF THE FUTURE

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Abstract

NASA's space missions of the future will be dominated by more moderato sized mini- and micro- spacecraft, Such missions will place stringent requirements on tho mass and powor consumption required for the various spacecraft subsystems, One of those subsystems is the communications subsystem.

This paper will prosent tho planning for, and technical progress on, optical communications technology to provide increased data communications capabilities for small spacecraft of the future. Characteristic mission design examples will be presented to illustrate the benefits of using laser beams as opposed to traditional RF signals for communications. Then a small optical communications terminal design program called the Optical Communications Demonstrator will be described. Finally, the design, developments and deployment planning for the ground reception infrastructure, will be discussed.

Background

The vast distances to deep space make data roturn via conventional radio-frequency techniques extremely difficult, As a result, current missions are severely limited in the amount of space-acquired data they can return, and future missions will require even mom link capacity. JPL has been developing the technology and systems designs for returning such information over laser beams. Communications at optical frequencies has a theoretical advantage over the currently used X-band communications of 71 dB, and will permit increases of 10-100 times in data rato capabilities while, at the same time, reducing the sizo and mass of tho hardwaro required on tho spacecraft and at the Earth receiver. These reductions, which aro extremely important for future mini and micro spacecraft missions, will eliminate the need for in-space deployable antennas on the spacecraft, and will allow more dosign flexibility for the placement and operational modes of tho vehicle's communications system.

Optical communications data can be returned either to an Earth-orbiting receiver, or directly to the ground, For ground-based reception, multiple-site diversity can be employed to circumvent cloud cover outages. Optical communication signals can also be sent to the spacecraft for commanding, ranging, or beacon-tracking purposes. Additionally, optical communications signals can be used scientifically to probe planetary atmospheres or characterize the interplanetary medium, in ways similar to how radio waves aro currently used to collect radio science information.

Development, demonstration and deployment planning activities have been underway for the past 13 years at the Jet Propulsion laboratory under NASA funding. Those activities include the technology developments for the spacecraft communications terminals, and for the Earth-vicinity reception systems. In the next section we will describe the benefits that optical communications provides to the future mini and micro-spacecraft missions of the future. Following this, the progress on a development program called the Optical Communications Demonstrator, a form, fit and function but laboratory-qualified engineering model of a spacecraft terminal, will be described, The final section describes preparation and planning activities for the Earth-reception end of the optical communications link,

Optical Communications Designs for Small Spacecraft

J PL's first activities in the "small spacecraft terminal" area started in 1989, In the mid 1980's, a study of a mission enhancement optical communications terminal for the Cassini mission was completed under a JPL contract to McDonnell Douglas. 1 his terminal design provided at least a factor of 5 improvement in data rate over the baselined RF communications link, but the technology was not sufficiently mature for the project to rely on optical as the only capability at that time. Furthermore, the mass of the package was too much for the project to carry along, in addition to the RF system, as an experiment. After a series of downscoping designs, the project manager finally said he would consider it only if the package mass could be less than 5 kg. At the time this appeared infeasible. However, since Cassini was planning on an Earth-gravity assist trajectory, we concluded that it was possible to do a downlink demonstration of optical communications from Cassini during that phase of the mission with a package that met that mass requirement, This resulted in the development of a package called the Small Cassini Optical Package Experiment (SCOPE).

The SCOPE package consisted of a laser diode transmitter that emitted 50 mW of light at 0.83 micrometers wavelength, some beam conditioning optics, a single two-axis steering mirror to point the beam, a quadrant detector to track an uplink beacon signal, and a dichroic beam splitter to separate the received beacon signal (used as a downlink pointing reference) from the transmitted signal. The optical portion of the SCOPE package had a mass of only 300 grams (including baseplate) and was capable of returning 1,000,000 bits of information per second to a 1-meter receiving telescope from twice the distance to the Moon. The supporting electronics were built and tested, and could have easily been packaged in a form that would have met the 5 kg limit. Other considerations later precluded this package from being included in the Cassini mission plan, but the activity served to refocus our thinking around much smaller optical communications terminals.

Since that time, many studies have been directed toward small spacecraft package designs. These have been brought on by the explosion of interest in micro/mini spacecraft programs like Pluto Flyby and the Discovery mission series. One of these studies was performed using the Pluto Flyby parameters.

Figure 1 shows the block diagram of the package designed for the Pluto Flyby example. It builds very strongly on the SCOPE package design. The major differences are the increase of the telescope size from 1 cm to 10 cm, the addition of a second transmit beam '(point ahead" mirror to compensate for cross velocity pointing aberrations, and replacement of the 50 mW diode laser transmitter with a 500 mW diode-pumped solid state laser transmitter.

A comparison of the performance of the optical and baselined RF systems for Pluto Flyby is shown in I-able 1. The RF system (at the time of the study) utilized a 1.47 meter RF antenna, a 3 Watt X-band transmitter, and assumed a 34 meter diameter DSN receiver station. The estimated communications system mass was 25.2 kg, the power consumption was 28 Watts, and the data rate returned from Pluto was only 40 bits/sec.

Contrast this with the optical system design which uses a 10 cm telescope (approximately the diameter of the subreflector on the X-band antenna), a 500 mW laser, and a 10-meter diameter receiving station. (NOTE: The receiving station is assumed to be a non-diffraction limited "photon bucket". Such systems are much less expensive than highly precise "imaging" telescopes like the Keck telescope. Photon bucket telescope designs are being very actively studied in another portion of the JPL optical communications program.) The package mass was estimated to be 8 kg, the power consumption 35 Watts, and the link can return 2000 bits/see from Pluto, In this design, minimization of the power consumption was not the primary objective since the mission will carry an RTG anyway. However, a second design was also performed where the data rate was reduced to 400 bits/see. In this case the mass and power estimates were reduced to 4.8 kg and 24,2 Watts respectively. 1 hese example serve to identify the substantial benefits afforded by optical communications technology.

Optical Communications Demonstrator Program

10 gain confidence in the maturity of the optical technology, it will be necessary to perform the necessary set of laboratory and then flight demonstrations. The early flight demonstrations will most likely be from near Earth orbit (perhaps the Space Shuttle or some other convenient host carrier), although airplane-to-ground demonstrations are also being considered. In anticipation of this, the portion of the optical communications program funded by NASA Code C was restructured 18 months ago to focus all of the efforts on the development of a system called the Optical Communications Demonstrator (OCD). The OCD program consists of three main parts. 1 he key element is the OCD Instrument which represents the spacecraft optical communications terminal. It is being designed as a laboratory model for a Earth-orbit spacecraft terminal capable of 100 Mbps data dump from orbit to ground, or as the breadboard model of a microspacecraft terminal for deep space, Supporting this are the OCD Control Terminal, which emulates a host spacecraft and provides for laboratory demonstration displays of system performance, and tile OCD Ground Station Simulator, which provides the necessary beacon signal and determines the performance of the transmitted optical beam from the OCD Instrument, Program planning and requirements generation were completed for the OCD program at the end of fiscal year 1992. During FY 93, the detailed design of the OCD Instrument has been performed. The fabrication of the OCD Instrument is scheduled for completion in FY 94.

1 he OCD Instrument architecture is based on a very simplified "reduced complexity design". 1 his architecture uses only one steering mirror and one detector assembly to accomplish uplink beacon signal acquisition and tracking, downlink transmit beam point-ahead, and transmit/receive path coalignment. 1 raditional designs have used up to four steering mirrors, three detector assemblies, and a large assortment of matching optics to accomplish theso same functions. A sketch of the telescope optical assembly of the OCD Instrument is shown in Figure 2. Mechanical packaging design of this structure is almost complete and fabrication should commence shortly.

As an extension of the OCD Instrument design, it was noticed that much of the architecture for the optical communications system is very similar to the designs of optical remote sensing instruments, such as imaging cameras, star trackers and imaging spectrometers. Accordingly, a preliminary design of a combined optical communications terminal, imaging camera and spectrometer has been completed. 1 his structure is shown in Figure 3. The combination of all these functions into a single instrument, all sharing a common telescope, would further reduce the size and mass impact on future small spacecraft.

Receiving System Technology and Planning

Technology development, system definition and deployment planning for the reception and processing of optical communications signals has been in progress since the program was started 13 years ago. Initially, these activities concentrated on conceptual design studies that identified the potential payoffs of the technology to prospective missions relative to the familiar RF technology. More recently the program has been focused around those activities that will provide the knowledge to accurately estimate the cost and performance predictions for future optical communications reception systems.

One of the most fundamental questions is whether the reception system can be located on the ground, or must be deployed in Earth orbit, Atmospheric cloud cover models predict that ground-based reception with multiple-site spatial diversity can achieve **throughput** availabilities of 9i'% or more. These results indicate that, at least for the short term, ground-based reception is more likely to be the most cost-effective approach. However, more detailed statistics of the cloud-induced signal fades and outages is needed to confirm this assertion.

I-o provide these statistics, a set of three autonomous visibility monitoring observatories has been developed and the observatories are in the process of being deployed. Placed at spatially separated locations around the southwest US, these observatories will track stars and measure their stellar intensities, both day and night. By combining the results of all three observatories, data on the joint correlation of the atmospheric cloud cover can be obtained.

A number of studies have also been conducted on the architecture of a ground-based optical reception system, or the resulting extension to an entire optical reception network. Most of these have concentrated on the definition of a Deep Space Optical Reception Antenna (DSORA), a facility that would be the optical equivalent of the current RF research and development station that supports the operational Deep Space Network, This facility, which contains a 1 O-meter diameter optical photon bucket aperture, is currently in the NASA Construction of Facilities plan and is scheduled for construction at the end of this decade (although the time schedule could be moved up if user needs dictated). Additionally, network deployment strategies are being studies as part of a Ground-Based Advanced Technology Study (GBAT S). 1 his study has identified placement strategies and has calculated the corresponding link performance availabilities.

Definition studies for Earth-orbiting optical reception stations have also been completed. Two two-year contractor studies, one with TRW and the other with Stanford Telecommunications Inc., have recently been completed. The study guidelines were to examine both RF and optical technology, select an appropriate wavelength, and then perform design, performance and cost estimation analyses. At the end of the first year, both contractors had concluded that if one goes to orbit for reception, it should be done in the optical region. At the beginning of the second year of the studies, both were given the authorization to focus only on the optical approach.

Computerized link analysis tools have also been developed. The first tool was an analysis program called OPT I which calculates the overall link performance for a direct detection optical link with a single photon counting detector, This was later modified to include an avalanche photodiode detector (OPTI-APD). Subsequent programs were then developed to analyze heterodyne optical communications reception links (HET), and to statistically evaluate the effects of component parameter value tolerances (TOLER) for direct detection links, These programs are all PC-based and can analyze links, or be used as link design aids, very efficiently.

Selected ground-based reception technologies have also beon developed. Spatial acquisition and tracking systems have been designed, analyzed and demonstrated. Additionally, very narrow optical filters that will bo required to block high background light levels during daytime reception are being developed and evaluated. These filters rely on an anomalous dispersion property of certain gases to produce a polarization rotation if the received signal is exactly on resonance with the gas **molecules.** Filters with passbands of less than 1 GHz (filter Q greater than 10^5), and with in-band transmissions in excess of 60%, have been built and tested.

Finally, a set of pathfinder demonstrations have been, or will soon be, completed. In December 1992, a very important uplink optical demonstration was conducted with the Galileo spacecraft. After the spacecraft passed by the Earth for gravity assist, and as it was speeding out toward Jupiter, laser beams wero simultaneously transmitted from two telescopes, one at JPL's Table Mountain Facility in California, and the other from the **Air** Force's Starfire Optical Rango in Albuquerque, NM. The spacecraft's imaging camera was used to receive the uplink optical signals by opening the camera shutter and scanning the camera in a direction parallel to tho Earth's terminator (the line which separates daylight from darkness). Successful signal detections were obtained on each of the seven experiment days and at spacecraft distances which ranged from 600,000 km to 6 million km. A follow-on demonstration to transmit atmospherically compensated (ie turbulence effects removed) beams to the corner cube retroreflectors on the moon is in preparation and will be conducted this fall. Other demonstrations, many of which involve various Air Force ground or space resources, are being discussed.

With the multitude of activities underway in this area, it is clear that the capability for receiving optical communications signals from space, whether from cooperative use of existing facilities or through the development and deployment of new ones, can be available **for** any planned demonstrations or operational use of the technology.

Conclusions

In this paper we have discussed sample mission design studies that show the benefits of optical communications to small spacecraft **missions** of the future. Wo then described a major development program for an Optical Communications Demonstrator, a laboratory model for a high data rato Earth-orbiter link terminal, or a microspacecraft terminal for a deep space vehicle. We then **covered the complementary** design, development and planning activities for the Earth-reception end of the link, This included a summary of several system-level optical communications demonstrations.

optical communications is a very rapidly maturing technology that is ideally suited **for the small spacecraft environment of the future, It not only offers a significant reduction** in the impact of the flight hardware on the host spacecraft, but a significant improvement in link channel capability as well. Laboratory models of the spacecraft hardware are being developed and the Earth-reception systems technology is progressing rapidly. The next most important step is to flight-validate the spacecraft technology. Programs to accomplish this are being studied and proposed.

Acknowledgement

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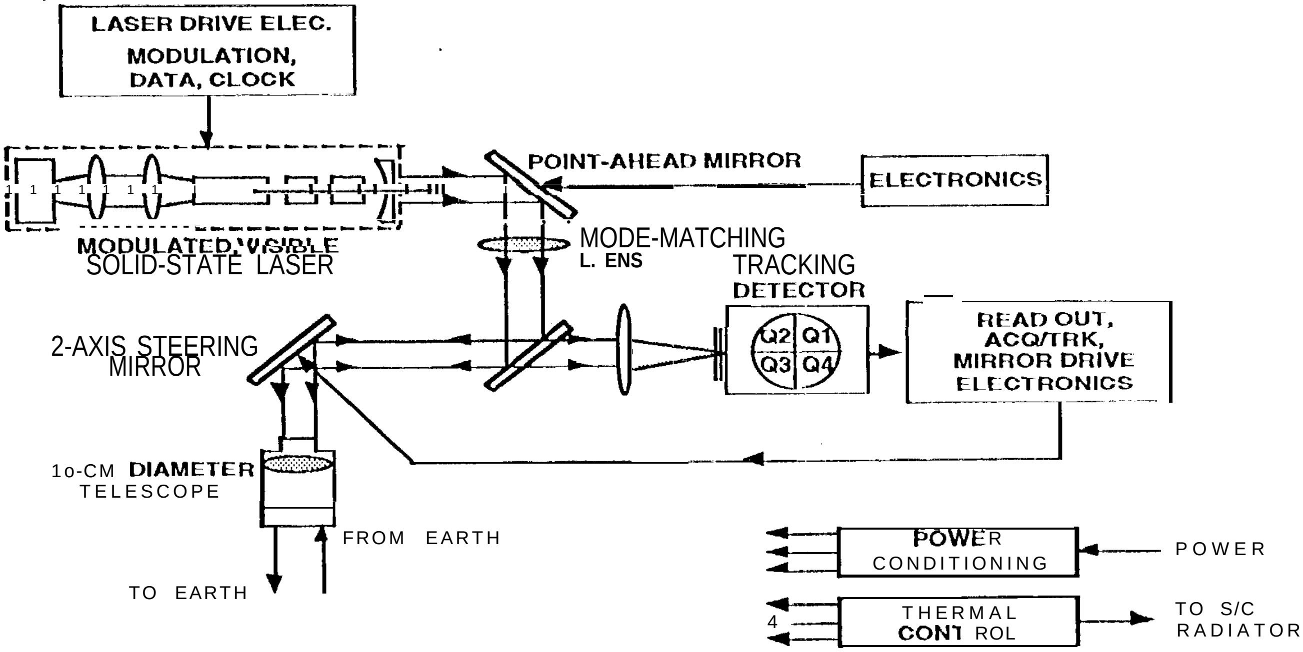

Figure 1. Block Diagram of the Pluto Flyby Design Example.

INPUT / OUTPUT PARAMETERS	OPTICAL LINK	RI (X-band) LINK
DATA RATE (WITH CODING)	2 kb/s	0.04 kb/s
DIAMETER OF TRANSMIT TELESCOPE	10 cm	347 cm
LINK DISTANCE	31 AU	31 AU
DIAMETER OF RECEIVE APERTURE	10 meters	34 meters
AVERAGE LASER OUTPUT POWER	0.5 watt	3.0 Watt
ATMOSPHERIC TRANSMISSION FACTOR	50 %	100 %
REQUIRED LINK BER (WITH CODING)	10^{-5}	Same
LINK MARGIN	3.6 dB	Same
MASS	8. 0 kg	25.2 kg
POWER CONSUMPTION	35 w	28 w

Table 1. Comparison of the optical and X-band communications parameters for the Pluto Flyby example.

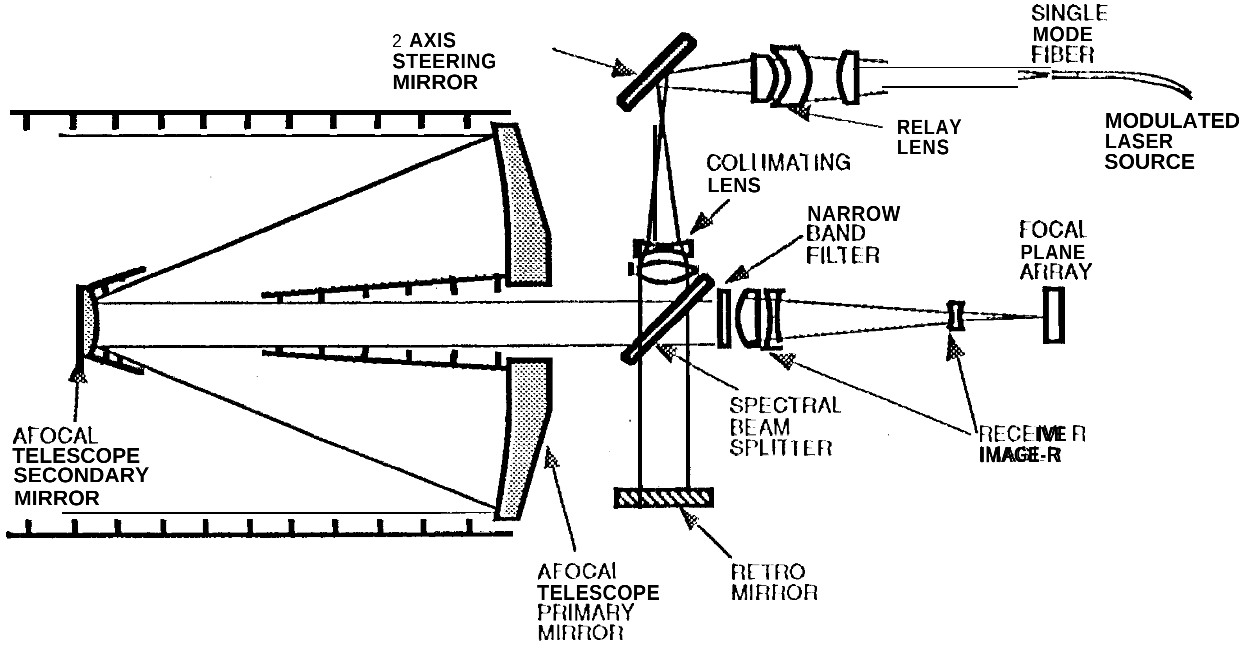

Figure 2. Layout of the Telescope Optical Assembly for the OCD Instrument.

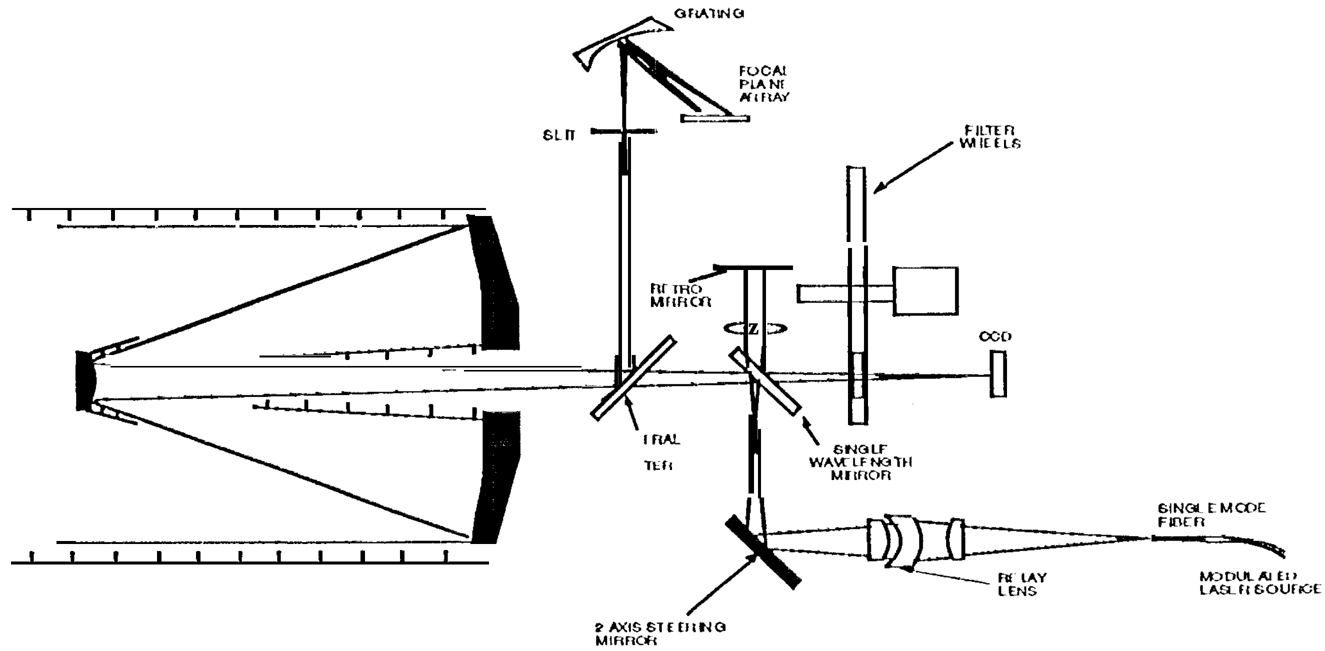

Figure 3. Optics layout of a combined optical communications terminal, imaging camera, and imaging spectrometer.